

RECOMBINANT FACTOR VIII HAVING INCREASED SPECIFIC ACTIVITY

[0001] This application claims the benefit of U.S. Provisional Patent Application Serial No. 60/526,664, filed December 3, 2003, which is hereby incorporated by reference in its entirety.

[0002] The present invention was made with funding received from the National Institutes of Health under grants HL 38199 and HL 30616. The U.S. government may retain certain rights in this invention.

FIELD OF THE INVENTION

[0003] The present invention relates to recombinant factor VIII having a specific activity that is higher than that of the corresponding wild-type factor VIII. The present invention also relates to methods of making and using the recombinant factor VIII.

BACKGROUND OF THE INVENTION

[0004] Factor VIII, a plasma protein that participates in the blood coagulation cascade, is decreased or defective in individuals with hemophilia A. Factor VIII functions as a cofactor for the serine protease factor IXa in the surface-dependent conversion of zymogen factor X to the serine protease, factor Xa (Davie, E.W., *Thromb. Haemost.* 74:1-6 (1995); Lollar, P., *Adv. Exp. Med. Biol.* 386:3-17 (1995)). Deficiency of factor VIII activity results in a marked reduction of factor IXa activity and in the subsequent rates of factor Xa generated during the propagation phase of coagulation.

[0005] Factor VIII is synthesized as an ~300-kDa single chain precursor protein (Wood et al., *Nature* 312:330-337 (1984); Toole et al., *Nature* 312:342-347 (1984)) with domain structure A1-A2-B-A3-C1-C2 (Vehar et al., *Nature* 312:337-342 (1984)). Factor VIII is processed to a series of divalent metal ion-linked heterodimers (Fass et al., *Blood* 59:594-600 (1982); Andersson et al., *Proc. Natl. Acad. Sci. U. S. A.* 83:2979-2983 (1986); Fay et al., *Biochim. Biophys. Acta* 871:268-278 (1986)) by cleavage at the B-A3 junction, generating a heavy chain

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(HC¹) minimally represented by the A1-A2 domains; and a light chain (LC) consisting of the A3-C1-C2 domains. The A domains of factor VIII share homology with the A domains of factor V and the copper-binding protein, ceruloplasmin (Church et al., *Proc. Natl. Acad. Sci. U. S. A.* 81:6934-6937 (1984)). One mol of copper has been identified in factor VIII (Bihoreau et al., *Eur. J. Biochem.* 220:41-48 (1994); Tagliavacca et al., *J. Biol. Chem.* 272:27428-27434 (1997)).

[0006] People with deficiencies in factor VIII or antibodies against factor VIII who are not treated with factor VIII suffer uncontrolled internal bleeding that may cause a range of serious symptoms, from inflammatory reactions in joints to early death. Severe hemophiliacs, who number about 10,000 in the United States, can be treated with infusion of human factor VIII, which will restore the blood's normal clotting ability if administered with sufficient frequency and concentration. The classic definition of factor VIII, in fact, is that substance present in normal blood plasma that corrects the clotting defect in plasma derived from individuals with hemophilia A.

[0007] The development of antibodies ("inhibitors" or "inhibitory antibodies") that inhibit the activity of factor VIII is a serious complication in the management of patients with hemophilia. Autoantibodies develop in approximately 20% of patients with hemophilia A in response to therapeutic infusions of factor VIII. In previously untreated patients with hemophilia A who develop inhibitors, the inhibitor usually develops within one year of treatment. Additionally, autoantibodies that inactivate factor VIII occasionally develop in individuals with previously normal factor VIII levels. If the inhibitor titer is low enough, patients can be managed by increasing the dose of factor VIII. However, often the inhibitor titer is so high that it cannot be overwhelmed by factor VIII. An alternative strategy is to bypass the need for factor VIII during normal hemostasis using factor IX complex preparations (for example, KONYNE[®], Proplex[®]) or recombinant human factor VIIa. Additionally, since porcine factor VIII usually has substantially less reactivity with inhibitors than human factor VIII, a partially purified porcine factor VIII preparation (HYATE:C[®]) is used. Many patients who have developed inhibitory antibodies to human factor VIII have been successfully treated with porcine factor VIII and have tolerated such

treatment for long periods of time. However, administration of porcine factor VIII is not a complete solution because inhibitors may develop to porcine factor VIII after one or more infusions.

[0008] Several preparations of human plasma-derived factor VIII of varying degrees of purity are available commercially for the treatment of hemophilia A. These include a partially-purified factor VIII derived from the pooled blood of many donors that is heat- and detergent-treated for viruses but contain a significant level of antigenic proteins; a monoclonal antibody-purified factor VIII that has lower levels of antigenic impurities and viral contamination; and recombinant human factor VIII, clinical trials for which are underway. Unfortunately, human factor VIII is unstable at physiologic concentrations and pH, is present in blood at an extremely low concentration (0.2 µg/ml plasma), and has low specific clotting activity.

[0009] Hemophiliacs require daily replacement of factor VIII to prevent bleeding and the resulting deforming hemophilic arthropathy. However, supplies have been inadequate and problems in therapeutic use occur due to difficulty in isolation and purification, immunogenicity, and the necessity of removing the AIDS and hepatitis infectivity risk. The use of recombinant human factor VIII or partially-purified porcine factor VIII will not resolve all the problems.

[0010] The problems associated with the commonly used, commercially available, plasma-derived factor VIII have stimulated significant interest in the development of a better factor VIII product. There is a need for a more potent factor VIII molecule so that more units of clotting activity can be delivered per molecule; a factor VIII molecule that is stable at a selected pH and physiologic concentration; a factor VIII molecule that is less apt to cause production of inhibitory antibodies; and a factor VIII molecule that evades immune detection in patients who have already acquired antibodies to human factor VIII.

[0011] The present invention is directed to overcoming these and other deficiencies in the art.

SUMMARY OF THE INVENTION

[0012] A first aspect of the present invention relates to a recombinant factor VIII having increased specific (or pro-coagulant) activity as compared to wild-type factor VIII. The recombinant factor VIII includes a point mutation in or near at least one calcium binding site of a wild-type factor VIII.

[0013] A second aspect of the present invention also relates to a pharmaceutical composition including the recombinant factor VIII of the present invention.

[0014] A third aspect of the present invention relates to an isolated nucleic acid molecule that encodes the recombinant factor VIII of the present invention.

[0015] A fourth aspect of the present invention relates to a recombinant DNA expression system that includes an isolated DNA molecule of the present invention, which expression system encodes a recombinant factor VIII.

[0016] A fifth aspect of the present invention relates to a host cell including an isolated nucleic acid molecule encoding the recombinant factor VIII of the present invention.

[0017] A sixth aspect of the present invention relates to a method of making a recombinant factor VIII having increased specific activity compared to that of a wild-type factor VIII. This method involves growing a host cell including an isolated nucleic acid molecule encoding the recombinant factor VIII of the present invention. The host cell is grown under conditions whereby the host cell expresses the recombinant factor VIII. Thereafter, the recombinant factor VIII is isolated.

[0018] A seventh aspect of the present invention relates to a method of making a recombinant factor VIII having increased specific activity compared to that of a wild-type factor VIII. This method involves altering the amino acid sequence of a wild-type factor VIII to yield a recombinant factor VIII. Alteration of the amino acid sequence of the wild-type factor VIII can include, for example, introducing at least one point mutation in or near at least one calcium binding site of the wild-type factor VIII. Thereafter, using protein analysis techniques well-known in the art, a determination can be made as to whether the recombinant

factor VIII has increased specific activity compared to that of the wild-type factor VIII.

[0019] An eighth aspect of the present invention relates to a method of treating an animal for hemophilia A. This method involves administering to an animal exhibiting hemophilia A an effective amount of the recombinant factor VIII of the present invention, whereby the animal exhibits effective blood clotting following vascular injury.

[0020] Applicants have surprisingly identified that the recombinant factor VIII of the present invention can differ in specific activity from the wild-type factor VIII. Factor VIII proteins having greater procoagulant activity from wild-type factor VIII are useful in treatment of hemophilia because lower dosages will be required to correct a patient's factor VIII deficiency. This will not only reduce medical expense for both the patient and the insurer, but also reduce the likelihood of developing an immune response to the factor VIII (because less antigen is administered).

BRIEF DESCRIPTION OF THE DRAWINGS

[0021] Figure 1 is a graph showing the effect of pre-incubation with Ca^{2+} on factor VIIIa reconstitution from isolated subunits. Factor VIII subunits (A1/A3-C1-C2 and A2) were separately pre-incubated with 3 mM Ca^{2+} or 0.1 mM EDTA for 18 hours. After mixing the pre-incubated A1/A3-C1-C2 and A2, reconstituted factor VIIIa activity was measured by a factor Xa generation assay as described in Example 2 (*infra*). Mixtures were A1/A3-C1-C2 pre-incubated with Ca^{2+} plus A2 pre-incubated with Ca^{2+} (closed circles), A1/A3-C1-C2 pre-incubated with EDTA plus A2 pre-incubated with Ca^{2+} (squares), A1/A3-C1-C2 pre-incubated with Ca^{2+} plus A2 pre-incubated with EDTA (triangles), and A1/A3-C1-C2 pre-incubated with EDTA plus A2 pre-incubated EDTA (open circles). Each point represents the average of four determinations.

[0022] Figure 2 shows the isothermal titration calorimetry of Ca^{2+} binding to the A1 subunit at 30°C. The top panel shows the heat signal for 30 injections of 2 μL aliquots of 2 mM Ca^{2+} into a 1.44 ml cell containing 25.6 μM A1. Both Ca^{2+} and A1 were in 10 mM MES, pH 6.5, 0.3 M KCl, 0.01% Tween 20. The bottom

panel shows the integrated heat for each injection after normalization to the amount of Ca^{2+} added. Lines were drawn from the curve fit using Origin software. The apparent thermodynamic parameters describing the fit are $n = 2.40 \pm 0.01$, $K_d = 0.74 \pm 0.05 \mu\text{M}$, and $\Delta H^0 = -4.76 \pm 0.03 \text{ kcal/mol}$. ΔS^0 was subsequently calculated as 12.3 cal/mol/K .

[0023] Figures 3A-3C are graphs showing factor VIII activity following titration with Ca^{2+} . B-domainless-factor VIII forms (50 nM) in the presence of the indicated amounts of free Ca^{2+} with 2 mM EGTA were incubated for 18 hours at 4°C and the factor VIII activity measured by a factor Xa generation assay as described in Example 2 (*infra*). Each point represents the average of four determinations. Figure 3A: High activity species include wild type (open circles), E113A (open triangles), and E115A (open squares). Figure 3B: Moderate activity species include E122A (open circles), E122D (open triangles), E124A (open squares), and D126A (closed circles). Figure 3C: Low activity species include E110A (open circles), E110D (open triangles), D116A (open squares), and D125A (closed circles). Lines were drawn from the curve fit according to a single-site binding model as described in Example 4 (*infra*).

[0024] Figures 4A-4C are graphs showing factor VIII activity following titration with Mn^{2+} . B-domainless factor VIII forms (50 nM) in the presence of the indicated amounts of free Mn^{2+} with 2 mM EGTA were assessed as described herein above with respect to Figures 3A-3C. Figure 4A: High activity species include wild type (open circles), E113A (open triangles), and E115A (open squares). Figure 4B: Moderate activity species include E122A (open circles), E122D (open triangles), E124A (open squares), and D126A (closed circles). Figure 4C: Low activity species include E110A (open circles), E110D (open triangles), D116A (open squares), and D125A (closed circles). Lines were drawn from the curve fit according to a single-site binding model as described in Example 4 (*infra*).

[0025] Figure 5 shows the sequence alignments of human factor V (SEQ ID NO:3) and human factor VIII (SEQ ID NO:4, which corresponds to residues 110-126 of SEQ ID NO:2). Residues are indicated by the single letter designation. Acidic residues are in bold typeface. Matched acidic residues are underlined.

[0026] Figure 6 shows the sequence alignments of residues 110-126 of the peptide sequences of factor VIII from human (SEQ ID NO:4), porcine (SEQ ID NO:5), murine (SEQ ID NO:6), and canine (SEQ ID NO:7). Amino acid residues are indicated using the single letter designation. Acidic residues are in bold and those homologous to factor V (SEQ ID NO:3) are underlined. E113 is conserved in all species.

[0027] Figure 7 is a graph showing clotting activity following saturation mutagenesis at E113. The single letter designation for amino acids corresponds to the substituted amino acid for each mutant. Activity is presented relative to a transfected wild type control normalized to a value = 1.

[0028] Figure 8 is a graph showing factor VIII activity following activation by thrombin.

[0029] Figures 9A and 9B are graphs showing factor VIII activity determined by a factor Xa generation assay on phospholipids vesicles. Figure 9A: Titration of factor IXa with factor VIIIa. Figure 9B: Titration of factor Xase complex with factor X.

[0030] Figures 10A and 10B are graphs showing factor VIII activity determined by a factor Xa generation assay on platelets. Figure 10A: Titration of factor IXa with factor VIIIa. Figure 10B: Titration of factor Xase complex with factor X.

DETAILED DESCRIPTION OF THE INVENTION

[0031] The present invention relates to a recombinant factor VIII having increased specific (or pro-coagulant) activity as compared to wild-type factor VIII. The recombinant factor VIII includes a point mutation in or near at least one calcium binding site of a wild-type factor VIII. As used herein, "in or near" means within about five amino acid residues from a residue that directly interacts with Ca^{2+} or Mn^{2+} ions.

[0032] The recombinant factor VIII of the present invention can be prepared by modifying the amino acid sequence of a wild-type factor VIII or a mutant factor VIII that has otherwise been modified to affect other properties of the factor VIII, such as antigenicity, circulating half-life, protein secretion, affinity

for factor IXa and/or factor X, altered factor VIII-inactivation cleavage sites, stability of the activated factor VIII form, immunogenicity, shelf-life, etc.

[0033] Suitable wild-type factor VIII that can be modified in accordance with the present invention can be from various animals including, without limitation, mammals such as humans (see, e.g., GenBank Accession Nos. AAA52484 (amino acid) and K01740 (nucleotide); and GenBank Accession Nos. CAD97566 (amino acid) and AX746360 (nucleotide), which are hereby incorporated by reference in their entirety), rats (see, e.g., GenBank Accession Nos. AAQ21580 (amino acid) and AY362193 (nucleotide), which are hereby incorporated by reference in their entirety), mice (see, e.g., GenBank Accession Nos. AAA37385 (amino acid) and L05573 (nucleotide), which are hereby incorporated by reference in their entirety), guinea pigs, dogs (see, e.g., GenBank Accession Nos. AAB87412 (amino acid) and AF016234 (nucleotide); and GenBank Accession Nos. AAC05384 (amino acid) and AF049489 (nucleotide), which are hereby incorporated by reference in their entirety), cats, monkeys, chimpanzees (see, e.g., GenBank Accession Nos. XP_529212 (amino acid) and XM_529212 (nucleotide), which are hereby incorporated by reference in their entirety), orangutans, cows, horses, sheep, pigs (see, e.g., GenBank Accession Nos. NP_999332 (amino acid) and NM_214167 (nucleotide), which are hereby incorporated by reference in their entirety), goats, rabbits, and chickens. These and other sequences are also available electronically via the Haemophilia A Mutation, Structure, Test and Resource Site (or HAMSTeRS), which further provides an alignment of human, porcine, murine, and canine factor VIII proteins. Thus, the conservation and homology among mammalian factor VIII proteins is well known.

[0034] By way of example, the human factor VIII cDNA nucleotide and predicted amino acid sequences are shown below in SEQ ID NOs: 1 and 2, respectively. Human factor VIII is synthesized as an approximately 300 kDa single chain protein with internal sequence homology that defines the "domain" sequence NH₂-A1-A2-B-A3-C1-C2-COOH. In a factor VIII molecule, a "domain," as used herein, is a continuous sequence of amino acids that is defined by internal amino acid sequence identity and sites of proteolytic cleavage by thrombin. Unless otherwise specified, factor VIII domains include the following

amino acid residues, when the sequences are aligned with the human amino acid sequence (SEQ ID NO: 2):

A1, residues Ala₁-Arg₃₇₂;

A2, residues Ser₃₇₃-Arg₇₄₀;

B, residues Ser₇₄₁-Arg₁₆₄₈;

A3, residues Ser₁₆₉₀-Ile₂₀₃₂;

C1, residues Arg₂₀₃₃-Asn₂₁₇₂; and

C2, residues Ser₂₁₇₃-Tyr₂₃₃₂.

[0035] The A3-C1-C2 sequence includes residues Ser₁₆₉₀-Tyr₂₃₃₂. The remaining sequence, residues Glu₁₆₄₉-Arg₁₆₈₉, is usually referred to as the factor VIII light chain activation peptide. Factor VIII is proteolytically activated by thrombin or factor Xa, which dissociates it from von Willebrand factor, forming factor VIIIa, which has procoagulant function. The biological function of factor VIIIa is to increase the catalytic efficiency of factor IXa toward factor X activation by several orders of magnitude. Thrombin-activated factor VIIIa is a 160 kDa A1/A2/A3-C1-C2 heterotrimer that forms a complex with factor IXa and factor X on the surface of platelets or monocytes. A "partial domain" as used herein is a continuous sequence of amino acids forming part of a domain.

[0036] The gene encoding the wild-type human factor VIII has a nucleotide sequence of SEQ ID NO:1, as follows:

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gccaccagaagatactacctgggtgcagtgggaactgtcatgggactatatgcaa
agtgatctcggtgagctgcctgtggacgcaagatttcctcctagagtgccaaaa
tcttttccattcaacacctcagtcgtgtacaaaaagactctgtttgtagaattc
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 taccttcgaattcaccaccagagttgggtgcaccagattgccctgaggatggag
 gttctgggctgcgaggcacaggaccttactga

[0037] The wild-type human factor VIII encoded by SEQ ID NO:1 has an amino acid sequence of SEQ ID NO:2, as follows:

ATRRYYLGAVELSWDYMQSDLGELPVDARFPFPRVPKSFNFNTSVVYKKTLEVEF
 TVHLEFNIAKPRPPWMGLLGPTIQAEVYDVTVITLKNMASHPVSLHAVGVSYWKA
 SEGA~~EYDDQTSQREKEDDKV~~FPGGSHTYVWQVLKENGPMASDPLCLTYSYLSHV
 DLVKDLNSGLIGALLVCREGSLAKEKTQTLHKFILLFAVFDEGKSWHSETKNSL
 MQDRDAASARAWPKMHTVNGYVNRSLPGLIGCHRKS~~VYWHVIGMGT~~PEVHSIF
 LEGHTFLVRNHRQASLEISPITFLTAQTL~~LLMDLGQFL~~FCHISSHQHDGMEAYV
 KVDS~~CP~~EEPQLRMKNNEEAEDYDDDLTDSEMDVVR~~FR~~DDDNSPSFIQIRSVAKKH

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PKTWVHYIAAEEEDWDYAPLV LAPDDRSYKSQYLNNGPQIRGRKYKKVRFMAYT
 DETFKTREAIQHESGILGPLLYGEVGD TLLIIFKNQASRPYNIYPHGITDVRPL
 YSRRLPKGVKHLKDFPILPGEIFKYKWTVTVEDGPTKSDPRCLTRYSSFVNME
 RDLASGLIGPLLYCYKESVDQGRNQIMSDKRNVLFSVFDENRSWYLTENIQRF
 LPNPAGVQLEDPEFQASNIMHSINGYVFDSLQLSVCLHEVAYWYILSIGAQ TDF
 LSVFFSGYT FKHKVMYEDTLTLFPFSGETVFM SMENPGLWILGCHNSDFRNRGM
 TALLKVSSCDKNTGDYEDSYEDISAYLLSKNNAIEPRSFQNSRHPSTRQKQF
 NATTIPENDIEKTD PWFARHTPMPKIQNVSSDDLMLLRQSPTPHGLSLSDLQE
 AKYETFSDDPSPGAIDSNNLSSEMTHFRPQLHHS GDMVFTPE SGLQLRLNEKLG
 TTAATELKKLDFKVSSTSNLITIPSDNLAAGTDNTSSLGPPSPMPVHYDSQLD
 TTLFGKKSSPLTESGGPLSLSEENND SKLLESGLMNSQESSWGKNVSSTESGRL
 FKGKRAHG PALLTKDNALFKVSI SLLKTNKTSNNSATNRKTHIDGPSLLIENSP
 SVWQNI LESDTEFKKVTPLIHDRMLMDKNATALRLNHMSNKTSSKNMEMVQOK
 KEGPIPPDAQNPDM SFFKMLFLPESARWIQ RTHGKNSLNSGQGPSPKQLVSLGP
 EKSVEGQNFLSEKNKVVGKGEFTKDVGLKEMVFPSSRNLF LTNLNLHENNTH
 NOEKKIQEEIEKKETLIQENVVLPQIHTVTGTKNFMKNL FLLSTRQNVEGSYEG
 AYAPVLQDFRSLNDSTNR TKKHTAHFSKKGEEENLEGLGNQTKQIVEKYACTTR
 ISPNTSQQNFVTQ RSKRALKQFRLPLEETELEKRIIVDDTSTQWSKNMKHLTPS
 TLTQIDYNEKEKGAITQSPLSDCLTRSHSIPQANRSP LPIAKVSSFPSIRPIYL
 TRVLFQDNSSHLPAASYRK KDSGVQESSHFLQGA KKNL SLAILTLEMTGDQRE
 VGSLGTSATNSVTYKKVENTVLPKPDLPKTS GKVELLPKVHIYQKDLFPTETSN
 GSPGHLDLVEGSL LQGTEGAIKWNEANRPGKVPFLRVATESSAKTPSKLLDPLA
 WDNHYGTQIPKEEWKSQEKSP EKTAFKKKDTILSLNACESNHAI AAINEGQNKP
 EIEVTWAKQGRTERLCSQNPPVLKRHQREITRTTLQSDQEEIDYDDTISVEMKK
 EDFDIYDEDENQSPRSFQKKTRHYFIAAVERLWDYGMSSSPHVLNRNAQSGSVP
 QFKKVVFQEFTDGSFTQPLYRGELNEHLGLLGPYIRAEVEDNIMVTFRNQASRP
 YSFYSSLISYEEDQRQGAEP RKNFVKPNETKTYFWKVQH HMAPTKDEFDC KAWA
 YFSDVDLEKDVHSGLIGPLLVCHTNTLNPAHGRQVTVQEFALFFTIFDET KSWY
 FTE NMERNCRAPCNIQMEDPTFKENYRFHAINGYIMDTLPGLVMAQDQIRIRWYL
 LSMGSNENIHSIHFSGHVFTVRKKEEYKMALYNLYPGVFETVEMLP SKAGIWRV
 ECLIGEHLHAGMSTLFLVYSNKCQ TPLGMASGHIRD FQITASGQYGQWAPKLAR
 LHYSGSINAWSTKEPFSWIKVDLLAPMI IHGIKTQGARQKFSSLYISQFIIMYS
 LDGKKWQTYRGNSTGTLMVFFGNVDSSGIKHNI FNPPIIARYIRLHP THYSIRS
 TLRMELMGCDLNSCSMPLGMESKAISDAQITASSYFTNM FATWSPSKARLHLQG
 RSNAWRPQVNNPKEWLQVDFQKTMKVTVGVT TQGVKSLLTSMYVKEFLISSQDG
 HQWTLFFQNGKVVFQGNQDSFTPVVNSLDP LLLTRYLRIHPQSWVHQIALRME
 VLGCEAQDLY

[0038] Suitable calcium binding sites that are available for mutation in accordance with the present invention can be located within any one of the A1, A2, A3, C1, and/or C2 domains of the activated wild-type factor VIII. In a preferred embodiment, the calcium binding site is located in the A1 domain, particularly between residues 110-126 as identified (underlined) in SEQ ID NO: 2 above.

[0039] Exemplary recombinant factor VIII includes a point mutation involving a substitution of the glutamic acid residue at position 113 of SEQ ID NO: 2 (shown in bold typeface in SEQ ID NO: 2), with another residue that is other than aspartic acid. In particular, the substitutions at position 113 of SEQ ID NO: 2 can include, without limitation, the following substitutions: E113A, E113V, E113I, E113N, E113L, E113G, and E113M. Of these, the E113A

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substitution is preferred, having a specific activity that is at least about twice as great as wild-type factor VIII. The substitution at the E113 residue can also be made using the various modified forms and/or derivatives of the substituting amino acid residues noted above (see, e.g., *Chem Files*, Vol. 2, No. 4, "Unnatural Amino Acids II: The latest Update on New Tools for Drug Discovery" (available from Sigma-Aldrich), which is hereby incorporated by reference in its entirety). Thus, a preferred recombinant factor VIII according to the present invention includes an A1 domain that comprises one of the amino acid sequences of SEQ ID NO: 4-7, where the E113 residue has been mutated in accordance with the present invention.

[0040] Another property of the recombinant factor VIII of the present invention is its higher binding affinity for Ca^{2+} , Mn^{2+} , or possibly other cations as compared to that of the wild-type factor VIII.

[0041] Suitable mutant factor VIII sequences that can be modified in accordance with the present invention can also include any previously known or subsequently identified mutant factor VIII sequences that have modified properties with regard to various attributes, including, without limitation, antigenicity, circulating half-life, protein secretion, affinity for factor IXa and/or factor X, altered factor VIII-inactivation cleavage sites, stability of the activated factor VIII form, immunogenicity, and shelf-life.

[0042] One example of a suitable mutant factor VIII that can be modified in accordance with the present invention is a B-domainless factor VIII that contains amino acid residues 1-740 and 1690-2332 of SEQ ID NO: 2. (see, e.g., U.S. Patent No. 6,458,563 to Lollar, which is hereby incorporated by reference in its entirety). Preferably, the recombinant B-domainless factor VIII contains one of the substitutions at position 113 identified herein.

[0043] In one embodiment of the B-domainless recombinant factor VIII of the present invention, the B-domain is replaced by a DNA linker segment and at least one codon is replaced with a codon encoding an amino acid residue that has the same charge as a corresponding residue of porcine factor VIII (see, e.g., U.S. Patent Application Publication No. 2004/0197875 to Hauser et al., which is hereby incorporated by reference in its entirety).

[0044] In another embodiment of the B-domainless recombinant factor VIII of the present invention, the modified mutant factor VIII is encoded by a nucleotide sequence having a truncated factor IX intron 1 inserted in one or more locations (see, e.g., U.S. Patent No. 6,800,461 to Negrier and U.S. Patent No. 6,780,614 to Negrier, which are hereby incorporated by reference in their entirety). This recombinant factor VIII can be used for yielding higher production of the recombinant factor VIII *in vitro* as well as in a transfer vector for gene therapy (see, e.g., U.S. Patent No. 6,800,461 to Negrier, which is hereby incorporated by reference in its entirety). In a particular example of this embodiment, the recombinant factor VIII can be encoded by a nucleotide sequence having a truncated factor IX intron 1 inserted in two locations, and having a promoter that is suitable for driving expression in hematopoietic cell lines, and specifically in platelets (see, e.g., U.S. Patent No. 6,780,614 to Negrier, which is hereby incorporated by reference in its entirety).

[0045] A second example of a suitable mutant factor VIII that can be modified in accordance with the present invention is a chimeric human/animal factor VIII that contains one or more animal amino acid residues as substitution(s) for human amino acid residues that are responsible for the antigenicity of human factor VIII. In particular, animal (e.g., porcine) residue substitutions can include, without limitation, one or more of the following: R484A, R488G, P485A, L486S, Y487L, Y487A, S488A, S488L, R489A, R489S, R490G, L491S, P492L, P492A, K493A, G494S, V495A, K496M, H497L, L498S, K499M, D500A, F501A, P502L, I503M, L504M, P505A, G506A, E507G, I508M, I508A, M2199I, F2200L, L2252F, V2223A, K2227E, and/or L2251_ (U.S. Patent No. 5,859,204 to Lollar, U.S. Patent No. 6,770,744 to Lollar, and U.S. Patent Application Publication No. 2003/0166536 to Lollar, each of which is hereby incorporated by reference in its entirety). Preferably, the recombinant chimeric factor VIII contains one of the substitutions at position 113 identified herein.

[0046] A third example of a suitable mutant factor VIII that can be modified in accordance with the present invention is a factor VIII that is characterized by greater stability of activated factor VIII by virtue of fused A2 and A3 domains. In particular, a factor VIII can be modified by substituting cysteine residues at positions 664 and 1826, resulting in a mutant factor VIII that includes

a Cys664-Cys1826 disulfide bond that covalently links the A2 and A3 domains (Gale et al., "An Engineered Interdomain Disulfide Bond Stabilizes Human Blood Coagulation Factor VIIIa," *J. Thrombosis and Haemostasis* 1(9):1966-1971 (2003), which is hereby incorporated by reference in its entirety). Preferably, the recombinant fused domain (A2-A3) factor VIII contains one of the substitutions at position 113 identified herein.

[0047] A fourth example of a suitable mutant factor VIII that can be modified in accordance with the present invention is a factor VIII with altered inactivation cleavage sites (see, e.g., Amano et al., "Mutation at Either Arg336 or Arg562 in Factor VIII is Insufficient for Complete Resistance to Activated Protein C (APC)-Mediated Inactivation: Implications for the APC Resistance Test," *Thrombosis & Haemostasis* 79(3):557-63 (1998), which is hereby incorporated by reference in its entirety). These alterations can be used to decrease the mutant factor VIII's susceptibility to cleavage enzymes that normally inactivate the wild type factor VIII.

[0048] A fifth example of a suitable mutant factor VIII that can be modified in accordance with the present invention is a factor VIII that has enhanced affinity for factor IXa (see, e.g., Fay et al., "Factor VIIIa A2 Subunit Residues 558-565 Represent a Factor IXa Interactive Site," *J. Biol. Chem.* 269(32):20522-7 (1994); Bajaj et al., "Factor IXa: Factor VIIIa Interaction. Helix 330-338 of Factor IXa Interacts with Residues 558-565 and Spatially Adjacent Regions of the A2 Subunit of Factor VIIIa," *J. Biol. Chem.* 276(19):16302-9 (2001); and Lenting et al., "The Sequence Glu1811-Lys1818 of Human Blood Coagulation Factor VIII Comprises a Binding Site for Activated Factor IX," *J. Biol. Chem.* 271(4):1935-40 (1996), which are hereby incorporated by reference in their entirety) and/or factor X (see, e.g., Lapan et al., "Localization of a Factor X Interactive Site in the A1 Subunit of Factor VIIIa," *J. Biol. Chem.* 272:2082-88 (1997), which is hereby incorporated by reference in its entirety).

[0049] A sixth example of a suitable mutant factor VIII that can be modified in accordance with the present invention is a factor VIII that is modified to enhance secretion of the factor VIII (see, e.g., Swaroop et al., "Mutagenesis of a Potential Immunoglobulin-Binding Protein-Binding Site Enhances Secretion of

Coagulation Factor VIII," *J. Biol. Chem.* 272(39):24121-4 (1997), which is hereby incorporated by reference in its entirety).

[0050] A seventh example of a suitable mutant factor VIII that can be modified in accordance with the present invention is a factor VIII with an increased circulating half-life. This modification can be made using various approaches, including, without limitation, by reducing interactions with heparan sulfate (Sarafanov et al., "Cell Surface Heparan Sulfate Proteoglycans Participate in Factor VIII Catabolism Mediated by Low Density Lipoprotein Receptor-Related Protein," *J. Biol. Chem.* 276(15):11970-9 (2001), which is hereby incorporated by reference in its entirety) and/or low-density lipoprotein receptor-related protein ("LRP") (Saenko et al., "Role of the Low Density Lipoprotein-Related Protein Receptor in Mediation of Factor VIII Catabolism," *J. Biol. Chem.* 274(53):37685-92 (1999); and Lenting et al., "The Light Chain of Factor VIII Comprises a Binding Site for Low Density Lipoprotein Receptor-Related Protein," *J. Biol. Chem.* 274(34):23734-9 (1999), which are hereby incorporated by reference in their entirety).

[0051] An eighth example of a suitable mutant factor VIII that can be modified in accordance with the present invention is a modified factor VIII encoded by a nucleotide sequence modified to code for amino acids within known, existing epitopes to produce a recognition sequence for glycosylation at asparagines residues (see, e.g., U.S. Patent No. 6,759,216 to Lollar, which is hereby incorporated by reference in its entirety). The mutant factor VIII of this example can be useful in providing a modified factor VIII that escapes detection by existing inhibitory antibodies (low antigenicity factor VIII) and which decreases the likelihood of developing inhibitory antibodies (low immunogenicity factor VIII). In one particular embodiment of this example, the modified factor VIII is mutated to have a consensus amino acid sequence for N-linked glycosylation. An example of such a consensus sequence is N-X-S/T, where N is asparagine, X is any amino acid, and S/T stands for serine or threonine (see U.S. Patent No. 6,759,216 to Lollar, which is hereby incorporated by reference in its entirety).

[0052] A ninth example of a suitable mutant factor VIII that can be modified in accordance with the present invention is a modified factor VIII that is

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a procoagulant-active factor VIII having various mutations (see, e.g., U.S. Patent Application Publication No. 2004/0092442 to Kaufman et al., which is hereby incorporated by reference in its entirety). One example of this embodiment relates to a modified factor VIII that has been modified to (i) delete the von Willebrand factor binding site, (ii) add a mutation at Arg 740, and (iii) add an amino acid sequence spacer between the A2- and A3-domains, where the amino acid spacer is of a sufficient length so that upon activation, the procoagulant-active factor VIII protein becomes a heterodimer (see U.S. Patent Application Publication No. 2004/0092442 to Kaufman et al., which is hereby incorporated by reference in its entirety).

[0053] Further, the mutant factor VIII can be modified to take advantage of various advancements regarding recombinant coagulation factors generally (see, e.g., Saenko et al., "The Future of Recombinant Coagulation Factors," *J. Thrombosis and Haemostasis* 1:922-930 (2003), which is hereby incorporated by reference in its entirety).

[0054] The recombinant factor VIII of the present invention can be modified at position 113, as well as be modified to be B-domainless, to be chimeric, to have fused A2-A3 domains, to have altered inactivation cleavage sites, to have enhanced factor IXa and/or factor X affinity, to have enhanced secretion, to have an increased circulating half-life, to have mutant glycosylation sites, or to possess any two or more of such modifications in addition to the modification at position 113.

[0055] The recombinant factor VIII is preferably produced in a substantially pure form. In a particular embodiment, the substantially pure recombinant factor VIII is at least about 80% pure, more preferably at least 90% pure, most preferably at least 95% pure. A substantially pure recombinant factor VIII can be obtained by conventional techniques well known in the art. Typically, the substantially pure recombinant factor VIII is secreted into the growth medium of recombinant host cells. Alternatively, the substantially pure recombinant factor VIII is produced but not secreted into growth medium. In such cases, to isolate the substantially pure recombinant factor VIII, the host cell carrying a recombinant plasmid is propagated, lysed by sonication, heat, or chemical treatment, and the homogenate is centrifuged to remove cell debris. The

supernatant is then subjected to sequential ammonium sulfate precipitation. The fraction containing the substantially pure recombinant factor VIII is subjected to gel filtration in an appropriately sized dextran or polyacrylamide column to separate the recombinant factor VIII. If necessary, a protein fraction (containing the substantially pure recombinant factor VIII) may be further purified by high performance liquid chromatography ("HPLC").

[0056] Another aspect of the present invention relates to an isolated nucleic acid molecule that encodes the recombinant factor VIII of the present invention. The isolated nucleic acid molecule encoding the recombinant factor VIII can be either RNA or DNA.

[0057] In one embodiment, the isolated nucleic acid molecule can have a nucleotide sequence encoding the amino acid sequence of SEQ ID NO: 2 as modified with one of the substitutions at position 113 (i.e., possessing one to three nucleotide substitutions within codon 113 of SEQ ID NO: 1 (nt 337-339)).

[0058] In another embodiment, the isolated nucleic acid molecule can have a nucleotide sequence encoding a B-domainless factor VIII of the type described above, as modified with one of the substitutions at position 113.

[0059] In another embodiment, the isolated nucleic acid molecule can have a nucleotide sequence encoding a chimeric human/porcine of the type described above, as modified with one of the substitutions at position 113.

[0060] In a further embodiment, the isolated nucleic acid molecule can have a nucleotide sequence encoding a fused A2-A3 domain factor VIII of the type described above, as modified with one of the substitutions at position 113.

[0061] In another embodiment, the isolated nucleic acid molecule can have a nucleotide sequence encoding a factor VIII whose inactivation sites have been modified as described above, as further modified with one of the substitutions at position 113.

[0062] In yet another embodiment, the isolated nucleic acid molecule can have a nucleotide sequence encoding a factor VIII whose affinity for factor IXa and/or factor X has been enhanced, as further modified with one of the substitutions at position 113.

[0063] In a still further embodiment, the isolated nucleic acid molecule can have a nucleotide sequence encoding a factor VIII whose affinity for various

serum-binding proteins has been altered to increase its circulating half-life, as further modified with one of the substitutions at position 113.

[0064] In a further embodiment, the isolated nucleic acid molecule can have a nucleotide sequence encoding a factor VIII that has increased secretion in culture, as further modified with one of the substitutions at position 113.

[0065] In a further embodiment, the isolated nucleic acid molecule can have a nucleotide sequence encoding a factor VIII that possesses one or more non-naturally occurring glycosylation site, as further modified with one of the substitutions at position 113.

[0066] In yet another embodiment, the isolated nucleic acid molecule encodes a recombinant factor VIII that is modified at position 113 and is also modified to possess any two or more of the following: modified to be B-domainless, modified to be chimeric, modified to have fused A2-A3 domains, modified to have altered inactivation cleavage sites, modified to have enhanced factor IXa and/or factor X affinity, modified to have enhanced secretion, modified to have an increased circulating half-life, and modified to possess one or more non-naturally occurring glycosylation site.

[0067] Another aspect of the present invention relates to a recombinant DNA expression system that includes an isolated DNA molecule of the present invention, which expression system encodes a recombinant factor VIII. In one embodiment, the DNA molecule is in sense orientation relative to a promoter.

[0068] A further aspect of the present invention relates to a host cell including an isolated nucleic acid molecule encoding the recombinant factor VIII of the present invention. In a particular embodiment, the host cell can contain the isolated nucleic acid molecule in DNA molecule form, either as a stable plasmid or as a stable insertion or integration into the host cell genome. In another embodiment, the host cell can contain a DNA molecule in an expression system. Suitable host cells can be, without limitation, animal cells (e.g., baby hamster kidney ("BHK") cells), bacterial cells (e.g., *E. coli*), insect cells (e.g., Sf9 cells), fungal cells, yeast cells (e.g., *Saccharomyces* or *Schizosaccharomyces*), plant cells (e.g., *Arabidopsis* or tobacco cells), or algal cells.

[0069] The recombinant DNA expression system and host cells can be produced using various recombinant techniques well-known in the art, as further discussed below.

[0070] The DNA molecule encoding the recombinant factor VIII of the present invention can be incorporated in cells using conventional recombinant DNA technology. Generally, this involves inserting the DNA molecule into an expression system to which the DNA molecule is heterologous (i.e., not normally present). The heterologous DNA molecule is inserted into the expression system or vector in sense orientation and correct reading frame. The vector contains the necessary elements for the transcription and translation of the inserted protein-coding sequences. Thus, one embodiment of the present invention provides a DNA construct containing the isolated nucleic acid of the present invention, which is operably linked to both a 5' promoter and a 3' regulatory region (i.e., transcription terminator) capable of affording transcription and expression of the encoded recombinant factor VIII of the present invention in host cells or host organisms.

[0071] With respect to the recombinant expression system of the present invention, an expression vector containing a DNA molecule encoding the recombinant factor VIII of the present invention can be made using common techniques in the art. The nucleic acid molecules of the present invention can be inserted into any of the many available expression vectors using reagents that are well known in the art. In preparing a DNA vector for expression, the various DNA sequences may normally be inserted or substituted into a bacterial plasmid. Any convenient plasmid may be employed, which will be characterized by having a bacterial replication system, a marker which allows for selection in a bacterium, and generally one or more unique, conveniently located restriction sites. The selection of a vector will depend on the preferred transformation technique and target host for transformation.

[0072] A variety of host-vector systems may be utilized to express the recombinant factor VIII-encoding sequence(s). Primarily, the vector system must be compatible with the host cell used. Host-vector systems include but are not limited to the following: bacteria transformed with bacteriophage DNA, plasmid DNA, or cosmid DNA; microorganisms such as yeast containing yeast vectors;

mammalian cell systems infected with virus (e.g., vaccinia virus, adenovirus, adeno-associated virus, etc.); insect cell systems infected with virus (e.g., baculovirus); and plant cells infected by bacteria (e.g., *Agrobacterium*). The expression elements of these vectors vary in their strength and specificities. Depending upon the host-vector system utilized, any one of a number of suitable transcription and translation elements can be used.

[0073] When recombinantly produced, the factor VIII protein or polypeptide (or fragment or variant thereof) is expressed in a recombinant host cell, typically, although not exclusively, a eukaryote.

[0074] Suitable vectors for practicing the present invention include, but are not limited to, the following viral vectors such as lambda vector system gt11, gtWES.tB, Charon 4, and plasmid vectors such as pCMV, pBR322, pBR325, pACYC177, pACYC184, pUC8, pUC9, pUC18, pUC19, pLG339, pR290, pKC37, pKC101, SV 40, pBluescript II SK +/- or KS +/- (see "Stratagene Cloning Systems" Catalog (1993)), pQE, pIH821, pGEX, pET series (Studier et al, "Use of T7 RNA Polymerase to Direct Expression of Cloned Genes," *Methods in Enzymology* 185:60-89 (1990), which is hereby incorporated by reference in its entirety), and any derivatives thereof. Any appropriate vectors now known or later described for genetic transformation are suitable for use with the present invention.

[0075] Recombinant molecules can be introduced into cells *via* transformation, particularly transduction, conjugation, mobilization, or electroporation. The DNA sequences are cloned into the vector using standard cloning procedures in the art, as described by Maniatis et al., *Molecular Cloning: A Laboratory Manual*, Cold Springs Harbor, N.Y.: Cold Springs Laboratory, (1982), which is hereby incorporated by reference in its entirety.

[0076] U.S. Patent No. 4,237,224 issued to Cohen and Boyer, which is hereby incorporated by reference in its entirety, describes the production of expression systems in the form of recombinant plasmids using restriction enzyme cleavage and ligation with DNA ligase. These recombinant plasmids are then introduced by means of transformation and replicated in unicellular cultures including prokaryotic organisms and eukaryotic cells grown in tissue culture.

[0077] Different genetic signals and processing events control many levels of gene expression (e.g., DNA transcription and messenger RNA (mRNA) translation).

[0078] Transcription of DNA is dependent upon the presence of a promoter which is a DNA sequence that directs the binding of RNA polymerase and thereby promotes mRNA synthesis. The DNA sequences of eukaryotic promoters differ from those of prokaryotic promoters. Furthermore, eukaryotic promoters and accompanying genetic signals may not be recognized in or may not function in a prokaryotic system, and, further, prokaryotic promoters are not recognized and do not function in eukaryotic cells.

[0079] Similarly, translation of mRNA in prokaryotes depends upon the presence of the proper prokaryotic signals which differ from those of eukaryotes. Efficient translation of mRNA in prokaryotes requires a ribosome binding site called the Shine-Dalgarno ("SD") sequence on the mRNA. This sequence is a short nucleotide sequence of mRNA that is located before the start codon, usually AUG, which encodes the amino-terminal methionine of the protein. The SD sequences are complementary to the 3'-end of the 16S rRNA (ribosomal RNA) and probably promote binding of mRNA to ribosomes by duplexing with the rRNA to allow correct positioning of the ribosome. For a review on maximizing gene expression, see Roberts and Lauer, *Methods in Enzymology* 68:473 (1979), which is hereby incorporated by reference in its entirety.

[0080] Promoters vary in their "strength" (i.e., their ability to promote transcription). For the purposes of expressing a cloned gene, it is generally desirable to use strong promoters in order to obtain a high level of transcription and, hence, expression of the gene. Depending upon the host cell system utilized, any one of a number of suitable promoters may be used. For instance, when cloning in *Escherichia coli*, its bacteriophages, or plasmids, promoters such as the T7 phage promoter, *lac* promoter, *trp* promoter, *recA* promoter, ribosomal RNA promoter, the P_R and P_L promoters of coliphage lambda and others, including but not limited, to *lacUV5*, *ompF*, *bla*, *lpp*, and the like, may be used to direct high levels of transcription of adjacent DNA segments. Additionally, a hybrid *trp-lacUV5 (tac)* promoter or other *E. coli* promoters produced by recombinant DNA

or other synthetic DNA techniques may be used to provide for transcription of the inserted gene.

[0081] Bacterial host cell strains and expression vectors may be chosen which inhibit the action of the promoter unless specifically induced. In certain operations, the addition of specific inducers is necessary for efficient transcription of the inserted DNA. For example, the *lac* operon is induced by the addition of lactose or IPTG (isopropylthio-beta-D-galactoside). A variety of other operons, such as *trp*, *pro*, etc., are under different controls.

[0082] Specific initiation signals are also required for efficient gene transcription and translation in prokaryotic cells. These transcription and translation initiation signals may vary in "strength" as measured by the quantity of gene specific messenger RNA and protein synthesized, respectively. The DNA expression vector, which contains a promoter, may also contain any combination of various "strong" transcription and/or translation initiation signals. For instance, efficient translation in *E. coli* requires an SD sequence about 7-9 bases 5' to the initiation codon ("ATG") to provide a ribosome binding site. Thus, any SD-ATG combination that can be utilized by host cell ribosomes may be employed. Such combinations include but are not limited to the SD-ATG combination from the *cro* gene or the *N* gene of coliphage lambda, or from the *E. coli* tryptophan E, D, C, B or A genes. Additionally, any SD-ATG combination produced by recombinant DNA or other techniques involving incorporation of synthetic nucleotides may be used.

[0083] In one embodiment, the nucleic acid molecule of the present invention is incorporated into an appropriate vector in the sense direction, such that the open reading frame is properly oriented for the expression of the encoded protein under control of a promoter of choice. This involves the inclusion of the appropriate regulatory elements into the DNA-vector construct. These include non-translated regions of the vector, useful promoters, and 5' and 3' untranslated regions which interact with host cellular proteins to carry out transcription and translation. Such elements may vary in their strength and specificity. Depending on the vector system and host utilized, any number of suitable transcription and translation elements, including constitutive and inducible promoters, may be used.

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[0084] A constitutive promoter is a promoter that directs expression of a gene throughout the development and life of an organism.

[0085] An inducible promoter is a promoter that is capable of directly or indirectly activating transcription of one or more DNA sequences or genes in response to an inducer. In the absence of an inducer, the DNA sequences or genes will not be transcribed.

[0086] The DNA construct of the present invention can also include an operable 3' regulatory region, selected from among those which are capable of providing correct transcription termination and polyadenylation of mRNA for expression in the host cell of choice, operably linked to a DNA molecule which encodes for a protein of choice.

[0087] The vector of choice, promoter, and an appropriate 3' regulatory region can be ligated together to produce the DNA construct of the present invention using well known molecular cloning techniques as described in Sambrook et al., *Molecular Cloning: A Laboratory Manual*, Second Edition, Cold Spring Harbor Press, NY (1989), and Ausubel, F. M. et al. *Current Protocols in Molecular Biology*, New York, N.Y: John Wiley & Sons (1989), which are hereby incorporated by reference in their entirety.

[0088] As noted, one alternative to the use of prokaryotic host cells is the use of eukaryotic host cells, such as mammalian cells, which can also be used to recombinantly produce the recombinant factor VIII of the present invention. Mammalian cells suitable for carrying out the present invention include, among others: COS (e.g., ATCC No. CRL 1650 or 1651), BHK (e.g., ATCC No. CRL 6281), CHO (ATCC No. CCL 61), HeLa (e.g., ATCC No. CCL 2), 293 (ATCC No. 1573), CHOP, and NS-1 cells.

[0089] Suitable expression vectors for directing expression in mammalian cells generally include a promoter, as well as other transcription and translation control sequences known in the art. Common promoters include SV40, MMTV, metallothionein-1, adenovirus Ela, CMV, immediate early, immunoglobulin heavy chain promoter and enhancer, and RSV-LTR.

[0090] Once the DNA construct of the present invention has been prepared, it is ready to be incorporated into a host cell. Accordingly, another aspect of the present invention relates to a method of making a recombinant cell.

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Basically, this method is carried out by transforming a host cell with a DNA construct of the present invention under conditions effective to yield transcription of the DNA molecule in the host cell. Recombinant molecules can be introduced into cells via transformation, particularly transduction, conjugation, mobilization, or electroporation.

[0091] In view of the recombinant technology discussed herein, another aspect of the present invention relates to a method of making a recombinant factor VIII of the present invention. This method involves growing a host cell of the present invention under conditions whereby the host cell expresses the recombinant factor VIII. The recombinant factor VIII is then isolated. In one embodiment, the host cell is grown *in vitro* in a growth medium. In a particular embodiment, suitable growth media can include, without limitation, a growth medium containing a von Willebrand Factor (referred to herein as "VWF"). In this embodiment, the host cell can contain a transgene encoding a VWF or the VWF can be introduced to the growth medium as a supplement. VWF in the growth medium will allow for greater expression levels of the recombinant factor VIII. Once the recombinant factor VIII is secreted into the growth medium, it can then be isolated from the growth medium using techniques well-known by those of ordinary skill in the relevant recombinant DNA and protein arts (including those described herein). In another embodiment, the method of making the recombinant factor VIII of the present invention further involves disrupting the host cell prior to isolation of the recombinant factor VIII. In this embodiment, the recombinant factor VIII is isolated from cellular debris.

[0092] When an expression vector is used for purposes of *in vivo* transformation to induce factor VIII expression in a target cell, promoters of varying strength can be employed depending on the degree of enhancement desired. One of skill in the art can readily select appropriate mammalian promoters based on their strength as a promoter. Alternatively, an inducible promoter can be employed for purposes of controlling when expression or suppression of factor VIII is desired. One of skill in the art can readily select appropriate inducible mammalian promoters from those known in the art. Finally, tissue specific mammalian promoters can be selected to restrict the efficacy of any gene transformation system to a particular tissue. Tissue specific promoters are

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known in the art and can be selected based upon the tissue or cell type to be treated.

[0093] Another aspect of the present invention relates to a method of making a recombinant factor VIII having increased specific activity compared to that of a wild-type factor VIII. This method involves altering the amino acid sequence of a wild-type factor VIII to yield a recombinant factor VIII. Alteration of the amino acid sequence of the wild-type factor VIII can include, for example, introducing at least one point mutation in or near at least one calcium binding site of the wild-type factor VIII. Thereafter, using protein analysis techniques well-known in the art, a determination can be made as to whether the recombinant factor VIII has increased specific activity compared to that of the wild-type factor VIII.

[0094] Another aspect of the present invention relates to a method of treating an animal for a blood disorder such as hemophilia, particularly hemophilia A. This method involves administering to an animal exhibiting hemophilia A an effective amount of the recombinant factor VIII of the present invention, whereby the animal exhibits effective blood clotting following vascular injury. A suitable effective amount of the recombinant factor VIII can include, without limitation, between about 10 to about 50 units/kg body weight of the animal. The animal can be any mammal, but preferably a human, a rat, a mouse, a guinea pig, a dog, a cat, a monkey, a chimpanzee, an orangutan, a cow, a horse, a sheep, a pig, a goat, or a rabbit.

[0095] The recombinant factor VIII of the present invention can be used to treat uncontrolled bleeding due to factor VIII deficiency (e.g., intraarticular, intracranial, or gastrointestinal hemorrhage) in hemophiliacs with and without inhibitory antibodies and in patients with acquired factor VIII deficiency due to the development of inhibitory antibodies. In a particular embodiment, the recombinant factor VIII, alone, or in the form of a pharmaceutical composition (i.e., in combination with stabilizers, delivery vehicles, and/or carriers) is infused into patients intravenously according to the same procedure that is used for infusion of human or animal factor VIII.

[0096] Alternatively, or in addition thereto, the recombinant factor VIII can be administered by administering a viral vector such as an adeno-associated

virus (Gnatenko et al., *Br. J. Haematol.* 104:27-36 (1999), which is hereby incorporated by reference in its entirety), or by transplanting cells genetically engineered to produce the recombinant factor VIII, typically *via* implantation of a device containing such cells. Such transplantation typically involves using recombinant dermal fibroblasts, a non-viral approach (Roth et al., *New Engl. J. Med.* 344:1735-1742 (2001), which is hereby incorporated by reference in its entirety).

[0097] The treatment dosages of recombinant factor VIII that should be administered to a patient in need of such treatment will vary depending on the severity of the factor VIII deficiency. Generally, dosage level is adjusted in frequency, duration, and units in keeping with the severity and duration of each patient's bleeding episode. Accordingly, the recombinant factor VIII is included in a pharmaceutically acceptable carrier, delivery vehicle, or stabilizer in an amount sufficient to deliver to a patient a therapeutically effective amount of the protein to stop bleeding, as measured by standard clotting assays.

[0098] Factor VIII is classically defined as that substance present in normal blood plasma that corrects the clotting defect in plasma derived from individuals with hemophilia A. The coagulant activity *in vitro* of purified and partially-purified forms of factor VIII is used to calculate the dose of recombinant factor VIII for infusions in human patients and is a reliable indicator of activity recovered from patient plasma and of correction of the *in vivo* bleeding defect. There are no reported discrepancies between standard assay of novel factor VIII molecules *in vitro* and their behavior in the dog infusion model or in human patients, according to Lusher et al., *New Engl. J. Med.* 328:453-459 (1993); Pittman et al., *Blood* 79:389-397 (1992); and Brinkhous et al., *Proc. Natl. Acad. Sci.* 82:8752-8755 (1985), which are hereby incorporated by reference in their entirety.

[0099] Usually, the desired plasma factor VIII activity level to be achieved in the patient through administration of the recombinant factor VIII is in the range of 30-100% of normal. In one embodiment, administration of the therapeutic recombinant factor VIII is given intravenously at a preferred dosage in the range from about 5 to 50 units/kg body weight, and particularly in a range of 10-50 units/kg body weight, and further particularly at a dosage of 20-40 units/kg body

weight; the interval frequency is in the range from about 8 to 24 hours (in severely affected hemophiliacs); and the duration of treatment in days is in the range from 1 to 10 days or until the bleeding episode is resolved. See, e.g., Roberts, H. R., and M. R. Jones, "Hemophilia and Related Conditions--Congenital Deficiencies of Prothrombin (Factor II, Factor V, and Factors VII to XII)," Ch. 153, 1453-1474, 1460, in *Hematology*, Williams, W. J., et al., ed. (1990), which is hereby incorporated by reference in its entirety. Patients with inhibitors may require a different amount of recombinant factor VIII than their previous form of factor VIII. For example, patients may require less recombinant factor VIII because of its higher specific activity than the wild-type VIII and its decreased antibody reactivity. As in treatment with human or plasma-derived factor VIII, the amount of therapeutic recombinant factor VIII infused is defined by the one-stage factor VIII coagulation assay and, in selected instances, *in vivo* recovery is determined by measuring the factor VIII in the patient's plasma after infusion. It is to be understood that for any particular subject, specific dosage regimens should be adjusted over time according to the individual need and the professional judgment of the person administering or supervising the administration of the compositions, and that the concentration ranges set forth herein are exemplary only and are not intended to limit the scope or practice of the claimed recombinant factor VIII.

[0100] Treatment can take the form of a single intravenous administration of the recombinant factor VIII or periodic or continuous administration over an extended period of time, as required. Alternatively, therapeutic recombinant factor VIII can be administered subcutaneously or orally with liposomes in one or several doses at varying intervals of time.

[0101] The recombinant factor VIII can also be used to treat uncontrolled bleeding due to factor VIII deficiency in hemophiliacs who have developed antibodies to human factor VIII.

[0102] It has been demonstrated herein that the recombinant factor VIII of the present invention can differ in specific activity from the wild-type factor VIII. Factor VIII proteins having greater procoagulant activity from wild-type factor VIII are useful in treatment of hemophilia because lower dosages will be required to correct a patient's factor VIII deficiency. This will not only reduce medical expense for both the patient and the insurer, but also reduce the likelihood of

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developing an immune response to the factor VIII (because less antigen is administered).

EXAMPLES

Materials and Methods

[0103] Recombinant wild-type factor VIII (Kogenate™) was obtained from Bayer Corporation (Berkeley, CA). Phospholipid vesicles containing 20% phosphatidylserine (PS), 40% phosphatidylcholine (PC), and 40% phosphatidylethanolamine (PE) were prepared using octylglucoside as described previously (Mimms et al., *Biochemistry* 20:833-840 (1981), which is hereby incorporated by reference in its entirety). The reagents α -thrombin, factor IXa β , factor X, and factor Xa (Enzyme Research Laboratories, South Bend, IN), hirudin, phospholipids, MnCl₂ (Sigma, St. Louis, MO), and the chromogenic Xa substrate S-2765 (N- α -benzyloxycarbonyl-D-arginyl-glycyl-L-arginyl-*p*-nitroanilide-dihydrochloride) (DiaPharma, West Chester, OH) were purchased from the indicated vendors. The B domainless factor VIII (FVIIIHSQ) expression construct HSQ-MSAB-NotI-RENeo was obtained from Dr. Pete Lollar and John Healey (see, e.g., Barrow et al., *Blood* 97:169-174 (2001), which is hereby incorporated by reference in its entirety).

[0104] Factor VIII LC, HC, A1, and A2 subunits were isolated from factor VIII as previously described (Fay et al., *J. Biol. Chem.* 276:12434-12439 (2001), which is hereby incorporated by reference in its entirety). Proteins were dialyzed into 10 mM MES, 0.3 M KCl, 0.01% Tween-20, pH 6.5, and stored at -80°C.

Example 1 - Construction, Expression and Purification of B-Domainless Factor VIII Mutants

[0105] B domainless-factor VIII cDNA was restricted from the factor VIII expression construct HSQ-MSAB-NotI-RENeo, using the endonucleases XhoI and NotI, and cloned into the Bluescript II K/S⁻ vector. Factor VIII molecules bearing single point mutation of Glu110Ala, Glu110Asp, Glu113Ala, Asp115Ala, Asp116Ala, Glu122Ala, Glu122Asp, Glu124Ala, Asp125Ala, or Asp126Ala, were constructed. Mutations were introduced into the shuttle constructs using the

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Stratagene QuickChange site-directed mutagenesis kit (Stratagene, La Jolla, CA) as described in Jenkins et al., *Blood* 100:501-508 (2002), which is hereby incorporated by reference in its entirety. Upon confirmation of the presence of only the desired mutations by dideoxy-sequencing, the appropriate fragment was restricted and cloned back into the factor VIII expression construct. Presence of only the desired mutations was confirmed by a second round of dideoxy-sequencing (Integrated DNA Technologies, Coralville, IA).

[0106] The factor VIII expression vector constructs were transfected in BHK cells using FuGene6 (Roche, Indianapolis, IN). The selection, sub-cloning, and cloning of stable transfectants were performed by standard methods and the cloned cells were cultured in roller bottles (Jenkins et al., *Blood* 100:501-508 (2002), which is hereby incorporated by reference in its entirety). The conditioned media was collected daily and the expressed proteins were purified using a one-step chromatography scheme as follows. The conditioned medium (~0.3 L) was centrifuged at 3,000 x g for 20 min and the supernatant was filtered through 0.22 μ m filter. The pH of the filtrate was adjusted to 6.0 and material was loaded onto a column of SP-sepharose (5 ml; Amersham-Pharmacia) equilibrated with 10 mM MES, pH 6.0, 0.2 M NaCl, 0.01% Tween 20. After washing with 20 mM HEPES, pH 7.2, 0.2 M NaCl, 0.01 % Tween 20, the bound factor VIII was eluted by with 20 mM HEPES, pH 7.2, 0.8 M NaCl, 0.01 % Tween 20. Active fractions were detected using a one-stage clotting assay, pooled and dialyzed against 10 mM MES pH 6.5, 0.3 M KCl, 0.01 % Tween 20 in Chelex100 treated ddH₂O. Resultant factor VIII forms were typically >80% pure as judged by SDS-polyacrylamide gel electrophoresis with albumin representing the major contaminant. Factor VIII samples were quick frozen and stored at -80°C.

Example 2 - Factor Xa Generation Assays

[0107] The rate of conversion of factor X to factor Xa was monitored in a purified system (Lollar et al., *Methods Enzymol.* 222:128-143 (1993), which is hereby incorporated by reference in its entirety) according to the method previously described in Wakabayashi et al., *Biochemistry* 40:10293-10300 (2001); Wakabayashi et al., *Biochemistry* 41:8485-8492 (2002), which are hereby

incorporated by reference in their entirety. Activity was determined as the amount of factor Xa generated (nM) per minute and converted to a value per nM factor VIII.

Example 3 - Preincubation of Factor VIII Subunits with Ca^{2+}

[0108] Mixtures of A1 and A3-C1-C2 (2 μM and 1 μM , respectively, in 10 mM MES, 0.3 M KCl, 0.01% Tween-20, 0.01% BSA, pH 6.5) and A2 (10 μM in 20 mM HEPES, 0.05 M KCl, 0.01% Tween-20, 0.01% BSA, pH 7.2) were separately pre-incubated with 3 mM Ca^{2+} or 0.1 mM EDTA for 18 hour at 4°C. Reactions were initiated by mixing A1/A3-C1-C2 and A2 solutions at a final subunit concentration of 40/20/200 nM (A1/A3-C1-C2/A2) in 20 mM HEPES, 0.05 M KCl, 0.01% Tween 20, 0.01% BSA, pH 7.2 (residual Ca^{2+} and EDTA concentrations were 0.3 mM and 4 μM , respectively). At the indicated times, aliquots were removed and the activity was measured by the factor Xa generation assay.

Example 4 - Isothermal Titration Calorimetry for Ca^{2+} Binding on A1

[0109] Isothermal titration calorimetry (ITC) was performed to measure Ca^{2+} binding to the isolated A1 subunit using a VP-ITC MicroCalorimetry Systems Instrument (MicroCal, Northampton, MA). The concentration of A1 was determined by A_{280} value using an extinction coefficient = $58,350 \text{ cm}^{-1}\text{M}^{-1}$ based upon the amino acid sequence for the A1 domain (factor VIII residues 1-372) according to the method of Gill and von Hippel (Gill et al., *Anal. Biochem.* 182:319-326 (1989), which is hereby incorporated by reference in its entirety). A1 subunit (25.6 μM) was treated with 10 mM EDTA for 18 hours at 4°C, followed by a dialysis-against 10 mM MES, pH 6.5, 0.3 M KCl, 0.01% Tween20. The dialysis buffer was made using Chelex 100 treated H_2O and the system was extensively washed with Chelex 100-treated H_2O prior to use. Samples and buffers were degassed prior to analysis. The A1-containing solution was placed in a 1.44 ml sample cell. A 700 μL syringe loaded with 2 mM CaCl_2 in the same buffer was used for a series of automatic injections of 2 μL each into the A1 solution while mixing at a rate of 290 rpm at 30°C. The cumulative total of the

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heat evolved was plotted against the total Ca^{2+} concentration to produce a binding isotherm. Each injection was followed by a 240 s pause to allow the system to return to a baseline value. Since heat produced from dilution, as measured by injecting the Ca^{2+} solution into the sample cell containing only the buffer, was negligible, the uncorrected data was used for the analysis. An identical independent binding model was fit to the data and thermodynamic parameters [enthalpy (ΔH^0), K_d , and molar binding stoichiometry (n)] were determined by nonlinear least squares regression using the ORIGIN software. Subsequently Gibbs free energy (ΔG) and entropy (ΔS^0) were calculated from the fitted values.

Example 5 - Factor VIII Activity Titration Using Ca^{2+} - or Mn^{2+} - EGTA

[0110] EGTA buffer with free Ca^{2+} concentrations of 0- 6.5 mM and Mn^{2+} -EGTA buffer with free Mn^{2+} concentrations of 0- 0.75 mM in the presence of 2 mM EGTA were prepared as previously described (Wakabayashi et al., *Biochemistry* 41:8485-8492 (2002); Wakabayashi et al., *Biochemistry* 42:145-153 (2003), which are hereby incorporated by reference in their entirety). Wild type or mutant HSQ factor VIII (50 nM) was reacted in the Ca^{2+} -EGTA buffer or Mn^{2+} -EGTA buffer at 4°C for 18 hours and resultant factor VIII activity was measured using the factor Xa generation assay. Non-linear least squares regression analysis was performed according to a single-site binding model using the formula,

$$\text{Activity} = \frac{k \cdot [\text{Me}^{2+}]}{K_d + [\text{Me}^{2+}]} + C$$

where k is constant reflecting the metal ion induced activity, $[\text{Me}^{2+}]$ is either free Ca^{2+} or free Mn^{2+} concentration, K_d is the dissociation constant, and C is constant reflecting the basal activity in the absence of exogenous metal ion.

Example 6 - Enzyme-Linked Immunoabsorbant Assay

[0111] A sandwich ELISA was performed to measure the concentration of HSQ factor VIII proteins (Jenkins et al., *Blood* 100:501-508 (2002), which is

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hereby incorporated by reference in its entirety). The procedure employed ESH8 (anti-factor VIII LC antibody; American Diagnostica) as a capture antibody and biotinylated R8B12 (anti-factor VIII A2 antibody; Green Mountain Antibodies) as the detection antibody. Thus, the epitopes for these antibodies are far-removed from the sites of mutagenesis. The amount of bound factor VIII was determined optically using a streptavidin-linked horse radish peroxidase (Calbiochem) with the substrate O-phenylenediamine dihydrochloride (Calbiochem) as previously described (Jenkins et al., *Blood* 100:501-508 (2002), which is hereby incorporated by reference in its entirety). Purified commercial recombinant factor VIII was used as the standard to determine the concentration of the samples. Factor VIII specific activity was determined from one-stage clotting assays and ELISA and is expressed as units/ μ g.

Example 7 - Statistical Analysis

[0112] Nonlinear least-squares regression analysis was performed by Kaleidagraph (Synergy, Reading, PA) to obtain parameter values and standard deviations.

Example 8 - Preincubation of Factor VIII Subunits with Ca^{2+} or EDTA Followed by Activity Reconstitution

[0113] It was previously demonstrated that maximal cofactor activity was achieved only when both HC and LC were pre-incubated with Ca^{2+} (Wakabayashi et al., *Biochemistry* 41:8485-8492 (2002), which is hereby incorporated by reference in its entirety), suggesting that Ca^{2+} binding to both HC and LC was necessary to generate active factor VIII. A similar evaluation of factor VIIIa reconstitution from the isolated A1, A2, and A3-C1-C2 was performed to determine the Ca^{2+} requirement for the HC-derived A1 and A2 subunits in activity generation. The reconstitution of factor VIIIa is a two-step process with the initial association of A1 and A3-C1-C2 comprising the rate-limiting step and requiring several hours to complete (Regan et al., *J. Biol. Chem.* 270:8546-8552 (1995), which is hereby incorporated by reference in its entirety). Therefore, this first step was completed by mixing A1 and A3-C1-C2 subunits (2:1, mol:mol) in the

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presence of either 3 mM Ca^{2+} or 0.1 mM EDTA for 18 hours. Activity generation was then monitored following the addition of A2 subunit, which, like the other subunits, was pre-incubated with either 3 mM Ca^{2+} or 0.1 mM EDTA. The reconstituted A1/A3-C1-C2 dimer and A2 subunit were diluted 50-fold prior to reconstitution to prevent the EDTA-treated component from acquiring Ca^{2+} at the time of reconstitution. Furthermore, the reconstitution time course (30 min) was short enough so that the dissociation of Ca^{2+} from subunits upon their dilution was not a concern. Evaluation of the negative control (both A1/A3-C1-C2 dimer and A2 subunit pre-treated with EDTA) did not generate any activity over the reconstitution time course (Figure 1). On the other hand, recombining the Ca^{2+} -treated A1/A3-C1-C2 dimer and A2 subunit resulted in the rapid generation of factor VIIIa activity (Figure 1) that reached a maximal level within 10 min. When Ca^{2+} -treated A1/A3-C1-C2 was associated with EDTA-treated A2, the generated activity was similar to the positive control (~90% activity at 10 min and ~80% activity at 30 min). Assuming the association rates for Ca^{2+} binding on each subunit was similar, these data suggested that there was little if any contribution of Ca^{2+} binding to A2 subunit for activity generation. Consistent with this result was the failure to reconstitute factor VIIIa activity with the Ca^{2+} -treated A2 plus EDTA-treated dimer. These results, taken together with the earlier observation on the requirement for Ca^{2+} -binding to HC for efficient factor VIII reconstitution (Wakabayashi et al., *Biochemistry* 41:8485-8492 (2002), which is hereby incorporated by reference in its entirety) indicates that Ca^{2+} binding to A1 subunit is a prerequisite for activity generation.

Example 9 - Ca^{2+} Binding to A1 Detected by ITC

[0114] The binding of Ca^{2+} to isolated A1 subunit was directly examined using ITC. Initial Ca^{2+} injections into the A1-containing solution showed a large exothermic peak (Figure 2), providing direct evidence for binding of the metal ion to the factor VIIIa subunit. Data were fitted using an identical independent binding model for cautious interpretation. The apparent thermodynamic values obtained from the binding isotherm were $\Delta H^0 = -4.76 \pm 0.03$ kcal/mole and $K_d = 0.74 \pm 0.05$ μM . ΔS^0 and ΔG values were calculated as 12.3 kcal/mol/K and -8.5

kcal/mol, respectively. Thus, ΔH^0 comprised 56% of ΔG , indicating that there was nearly equal contribution of enthalpy and entropy to the free energy change following the binding of Ca^{2+} to the A1 subunit. The observation of a large entropy change upon Ca^{2+} binding to A1 suggested a complex mechanism likely involving a significant conformational component. Interestingly, a stoichiometry of 2.4 was obtained from the fitted data indicating the presence of more than one Ca^{2+} sites contained within the A1 subunit.

Example 10 - Factor VIII Mutations of a Putative Ca^{2+} -Binding Site in A1

[0115] The data presented in Examples 8 and 9 indicate the presence of a Ca^{2+} site(s) within the A1 domain of factor VIII that is (are) required for cofactor activity. Based upon the homology of factor VIII residues 110-126 to the residues comprising a putative Ca^{2+} -binding site localized in factor V, a series of point mutations were constructed where acidic residues were replaced with Ala (or in some cases Asp). The stable transfectants were expressed as B-domainless factor VIII in BHK cells and recombinant factor VIII was purified as described in Example 1 (*supra*). The freshly purified factor VIII preparations (mutants and wild type) were dialyzed against metal ion-free buffer, and specific activity values were determined by one-stage clotting and sandwich ELISA assays (Table 1).

Table 1: Specific Activity of Factor VIII Wild Type and Mutant Forms
Specific Activity

Wild Type	4.77 ± 0.54^a	(100.0) ^b
E110A	0.18 ± 0.03	(3.8)
E110D	0.48 ± 0.09	(10.1)
E113A	9.78 ± 0.03	(205.0)
D115A	5.04 ± 0.49	(105.5)
D116A	0.54 ± 0.02	(11.3)
E122A	0.58 ± 0.01	(12.2)
E122D	1.07 ± 0.24	(22.4)
E124A	2.11 ± 0.10	(44.3)
D125A	0.46 ± 0.01	(9.6)
D126A	0.59 ± 0.13	(12.5)

The activity and the concentration of each factor VIII preparation was measured by a one stage clotting assay and by ELISA, respectively, as described herein, and specific activity was calculated.

^aUnit/ μg

^bRelative activity (% of wild type)

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This treatment resulted in the retention of a significant level of activity, as judged by a specific activity of 4.8 units/ μ g for the wild type factor VIII, while removing exogenous metal ions from the protein preparations. The activity observed under these conditions likely reflected retention of a metal ion(s), possibly Ca^{2+} , which is (are) not readily released in the absence of chelators. This property is not due to the presence of single chain factor VIII (~30-50% of total factor VIII) in the recombinant preparations since partial purification of the factor VIII to enrich for single chain material yielded a similar specific activity as the unfractionated factor VIII preparation.

[0116] Several of the Ala-substituted point mutations (E110A, D116A, E122A, D125A, and D126A) exhibited marked reductions in specific activity to levels of ~4 to 12% of the wild type value (Table 1 (*supra*)). Thus the reduction in volume of the side chain and/or loss in electrostatic potential may result in slight conformational changes within this region that impair cofactor activity. Since results from a prior study evaluating a Ca^{2+} site in lactalbumin showed the importance of side chains when replacing critical residues (Anderson et al., *Biochemistry* 36:11648-11654 (1997), which is hereby incorporated by reference in its entirety), selected, additional mutants were made with the conservative substitution of Asp for Glu at residues 110 and 122. As shown in Table I (*supra*), significantly greater activity was retained in the E110D and E122D mutants (10.1 and 22.4%, respectively) compared with E110A and E122A mutants (3.8 and 12.2%, respectively).

Example 11 - Cofactor Activity Generated from Factor VIII Mutants Following Titration with Ca^{2+}

[0117] Prior studies examining Ca^{2+} binding in factor VIII employed isolated HC and LC prepared from the EDTA-treated heterodimer (Wakabayashi et al., *Biochemistry* 40:10293-10300 (2001); Wakabayashi et al., *Biochemistry* 41:8485-8492 (2002), which are hereby incorporated by reference in their entirety). Mixing of chains in the absence of Ca^{2+} resulted in no regenerated activity. As shown herein, limitations in the amounts of mutant factor VIII precluded chain separation and purification. However, it was observed that the basal activity of the factor VIII measured in the absence of exogenous metal could

be increased ~2-3-fold with saturating levels of Ca^{2+} . This incremental activity increase provided a functional assay for the binding of Ca^{2+} to the factor VIII A1 domain mutants.

[0118] Increases in cofactor activity for the factor VIII wild type and 110-126 mutants in the absence of exogenous metal ion was determined following titration with Ca^{2+} . Results are presented in Figure 3 and are arbitrarily divided into high (Figure 3A), moderate (Figure 3B) and low (Figure 3C) activity factor VIII forms. Estimated parameter values determined by nonlinear least-squares curve fitting are listed in Table 2 (*infra*). An optimized range of Ca^{2+} concentrations (0-6.5 mM) was selected to cover the complete change in activity for all factor VIII forms. No significant increase in activity at higher concentrations of Ca^{2+} (>10 mM) was observed. The k value indicates the difference between maximum activity at saturation with Ca^{2+} and minimum activity with no exogenous metal ion present (C value). Therefore, the k value was used as an indicator to assess the activity response for each mutant to added Ca^{2+} .

[0119] Wild type factor VIII and many factor VIII mutants displayed an increase in activity in response to increases in the concentration of Ca^{2+} . Maximal activity response for the wild type reflected a high affinity for Ca^{2+} ($K_d = 1.18 \mu\text{M}$, Table 2-1) and this value compared favorably with a $K_d = 8.9 \mu\text{M}$ for Ca^{2+} binding as measured in a functional assay for reconstituted factor VIII HC and LC (Wakabayashi et al., *Biochemistry* 41:8485-8492 (2002), which is hereby incorporated by reference in its entirety), as well as with the value determined above from ITC analysis of the isolated A1 subunit.

Table 2: Metal Ion Binding Parameters for Factor VIII Wild Type and Mutants

	Ca ²⁺ Binding Parameters		Mn ²⁺ Binding Parameters		C ^c (% of wild type)
	K _d (μM)	k	K _d (μM)	k	
Wild Type	1.18 ± 0.32	15.03 ± 1.09 ^a (100.0 ^b)	1.40 ± 0.24	12.37 ± 0.46 ^a (100.0 ^b)	20.08 ± 0.47 ^a (100.0 ^b)
E110A	n.d.	0.00 ± 0.00 (0.0)	0.09 ± 0.03	1.23 ± 0.13 (10.0)	0.64 ± 0.25 (3.2)
E110D	27.79 ± 12.88	1.29 ± 0.13 (8.6)	0.48 ± 0.14	1.95 ± 0.15 (15.8)	1.45 ± 0.16 (7.2)
E113A	0.71 ± 0.24	17.43 ± 1.77 (116.0)	0.39 ± 0.09	15.97 ± 0.99 (129.2)	24.55 ± 1.12 (122.3)
D115A	8.44 ± 1.32	13.72 ± 0.51 (91.3)	0.61 ± 0.25	11.88 ± 1.32 (96.0)	11.56 ± 1.70 (57.5)
D116A	40.38 ± 7.46	6.78 ± 0.27 (45.1)	11.15 ± 2.25	3.33 ± 0.17 (26.9)	3.87 ± 0.23 (19.3)
E122A	37.43 ± 4.00	9.60 ± 0.22 (63.9)	4.11 ± 0.89	6.50 ± 0.33 (52.5)	3.46 ± 0.23 (17.2)
E122D	3.80 ± 1.04	7.06 ± 0.46 (47.0)	1.57 ± 0.37	6.65 ± 0.35 (53.8)	4.76 ± 0.32 (23.7)
E124A	9.51 ± 1.48	9.60 ± 0.35 (63.9)	0.32 ± 0.12	8.71 ± 0.96 (70.5)	6.50 ± 2.07 (32.4)
D125A	n.d.	0.00 ± 0.00 (0.0)	n.d.	0.00 ± 0.00 (0.0)	8.21 ± 0.35 (40.9)
D126A	97.62 ± 18.79	2.18 ± 0.09 (14.5)	0.29 ± 0.11	6.70 ± 0.75 (54.1)	6.17 ± 0.99 (30.7)

Parameter values (k, C, and K_d) were calculated by non-linear least-square regression from the data shown in Figures 3 and 4 using the formula shown herein.
n.d., not determined.

^aFactor VIII activity is expressed as factor Xa generated (nM/min/nM factor VIII).

^bRelative activity (% of wild type)

^cC is the average of the estimated values obtained from Figures 3 and 4.

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[0120] Two mutations (E113A and E122D) showed little deviation from the wild-type affinity parameters. On the other hand, four of the factor VIII mutants tested, E110D, D116A, E122A, and D126A showed ~25-90-fold increases in K_d for Ca^{2+} binding compared to wild type, indicating a marked reduction in affinity for the metal ion and suggesting a possible role for these residues in forming a Ca^{2+} binding site. Comparison of the results obtained for E122D and E122A showing an ~3- and ~30-fold reduction in Ca^{2+} affinity suggested the conserved substitution was relatively benign compared with the Ala substitution. A similar disparity was observed for mutation at E110 where the Asp substitution yielded an ~25-fold reduction in affinity while substitution with Ala appeared to eliminate the Ca^{2+} binding site. These results suggested a significant role for these residues, especially E110, in Ca^{2+} binding. The loss of Ca^{2+} binding was also observed with mutation at D125. Based upon the observed defects in Ca^{2+} binding and/or affinity, it was proposed that residues E110, D116, E122, D125 and D126 form a Ca^{2+} -coordination site in the A1 domain of factor VIII. It was also speculated that E110 and D125 are critical to this site since alteration of these residues appeared to result in loss of Ca^{2+} binding. Furthermore, it was suggested that residues D115 and E124 make little contribution to Ca^{2+} coordination. The basis for this contention is the minimal effect of Ala substitution on Ca^{2+} binding at these sites, inasmuch as K_d values were increased by <9-fold. This modest reduction in affinity may arise from Ala substitution at these residues affecting the contributions of the adjacent residues D116 and D125, respectively to the Ca^{2+} -binding site.

**Example 12 - Cofactor Activity Generated from Factor VIII Mutants
Following Titration with Mn^{2+}**

[0121] In a recent report, it was shown that Mn^{2+} binds factor VIII with high affinity (5.7 μM) and results in similar stimulation of cofactor activity (Wakabayashi et al., *Biochemistry* 42:145-153 (2003), which is hereby incorporated by reference in its entirety). However, that study also revealed competition of Tb^{3+} binding to factor VIII by Mn^{2+} but not by Ca^{2+} , indicating that the Mn^{2+} and Ca^{2+} binding sites in factor VIII were not identical. In order to

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determine whether any of the residues we identify above as participating in binding Ca^{2+} contribute to forming a Mn^{2+} -binding site, a similar approach was employed where factor VIII activity was measured in response to titration with Mn^{2+} . Results of these studies are shown in Figure 4 and Table 2-2, and employed a range of Mn^{2+} concentrations from 0-0.75 mM (concentrations >5 mM resulted in no further increase in activity). Several parallels in the response to Ca^{2+} were observed using Mn^{2+} . Wild type factor VIII displayed a high affinity for Mn^{2+} ($K_d = 1.40 \mu\text{M}$). Most of the mutants showed an increase in activity following addition of Mn^{2+} , and activity values at saturating concentration of Mn^{2+} (k values) were very similar to those observed for Ca^{2+} . Thus the value for the activity response varied depending upon the particular mutation rather than the metal ion used to saturate the response, suggesting that the activity response could result from modest changes in conformation that were unrelated to the specific metal-ion binding event. Therefore, with respect to this particular site in the A1 domain, both Ca^{2+} and Mn^{2+} generate activity by a mechanism affecting a common region crucial for cofactor function.

[0122] In contrast, while markedly reduced Ca^{2+} affinities were observed for E122A and D126A, the affinity of these factor VIII mutations for Mn^{2+} was either only marginally (~ 2 -fold) reduced or unchanged, respectively. An ~ 8 -fold reduction in Mn^{2+} was observed for the mutant D116A (compared with a ~ 40 -fold reduction in Ca^{2+} affinity), and this result may suggest a role for D116 in the coordination of Mn^{2+} . Interestingly, the two mutations that showed little if any response to Ca^{2+} (E110A and D125A) were also unresponsive to Mn^{2+} . Substitution of Asp for Glu at residue 110 partially restored Ca^{2+} -dependent function but had little effect on the Mn^{2+} -dependent activity, suggesting that this residue does not likely function in binding Mn^{2+} . While mutations at E110 showed marginal activity relative to wild type in the absence of exogenous metal ion ($C = 3.2\%$ and 7.2% for Ala and Asp substitutions), the mutation D125A retained significant activity ($C = 41\%$). This observation indicated that mutation at D125 did not likely result in any global change in conformation that would diminish factor VIII activity. This observation adds strong support to the conclusion that D125 participates in the coordination of either Ca^{2+} or Mn^{2+} .

Discussion of Examples 1-12

[0123] Previously, it was found that Ca^{2+} (or Mn^{2+}) binding to factor VIII HC was essential for cofactor activity (Wakabayashi et al., *Biochemistry* 41:8485-8492 (2002); Wakabayashi et al., *Biochemistry* 42:145-153 (2003), which are hereby incorporated by reference in their entirety). A Ca^{2+} -binding site in the A1 domain of factor VIII has now been identified and tentatively localized. The occupancy of this binding site yields an increase in specific activity. Furthermore, the observation that Ca^{2+} binding to A2 domain in HC contributes little if at all to generate cofactor activity highlights the functional role of the Ca^{2+} binding site in A1 domain in HC. Recently, Zeibdawi et al. (Zeibdawi et al., *J. Biol. Chem.* 276:19929-19936 (2001), which is hereby incorporated by reference in its entirety) reported that residues 94-110 in factor V comprise a Ca^{2+} binding site required for its activity. In the present application, the homologous region in the A1 domain of factor VIII (residues 110-126) for Ca^{2+} binding was probed using a site-directed mutagenesis approach. Results show that mutation at each of several acidic amino acids (E110, D116, E122, D125, and D126) caused a marked reduction (or complete loss) of Ca^{2+} binding affinity, providing evidence that these residues participate in coordinating Ca^{2+} . In addition, data from a complementary study revealed that in the absence of Ca^{2+} , D125 (and possibly D116) likely contribute to the coordination of Mn^{2+} . Thus, these results are consistent with an earlier report showing that Ca^{2+} and Mn^{2+} bind to non-identical sites in HC (Wakabayashi et al., *Biochemistry* 42:145-153 (2003), which is hereby incorporated by reference in its entirety) and further suggest that these sites are in close proximity to one-another.

[0124] Mechanism(s) by which Ca^{2+} (or Mn^{2+}) generate active factor VIII remain largely unknown. The factor VIII A domain homology model (Pemberton et al., *Blood* 89:2413-2421 (1997), which is hereby incorporated by reference in its entirety) predicts residues 102-116 not to possess a defined secondary structure while residues 120-125 form an α -helix with a short β strand segment (residues 117-119) connecting the two segments. Based upon the results presented herein, it has been proposed that Ca^{2+} stabilizes this region by forming bonds with E110, D116, E122, D125, and/or D126. This coordination would provide appropriate

energy to fix in space the elongated region defined by 110-116. Furthermore, it is of interest to note that in the 5-domainal factor VIII model (Stoilova-McPhie et al., *Blood* 99:1215-1223 (2002), which is hereby incorporated by reference in its entirety), this region juxtaposes the C1 domain. While A1 and A3 domains appear to associate with a relatively extended interface, the interface between A1 and C1 is small. Thus, it can be that stabilizing a segment in A1 near C1 may add structure to a "hinge" region separating the A and C domains.

[0125] The above hypothesis is reinforced by the results obtained with Mn^{2+} , which is typically coordinated by acidic residues and/or His residues (Bertini et al., *Handbook on Metalloproteins*, New York, NY:Marcel Dekker, Inc. (2001), which is hereby incorporated by reference in its entirety). There are two His residues in C1 (H2082 and H2137) that are in close proximity to residues 110-126 in A1. It is proposed that these His residues contribute to Mn^{2+} coordination with D125 (and possibly D116). The result of this coordination could also stabilize the interaction of A1 and C1 by bridging these regions. This explanation is compatible with the results showing that Ca^{2+} and Mn^{2+} bind different sites (Wakabayashi et al., *Biochemistry* 42:145-153 (2003), which is hereby incorporated by reference in its entirety) yet generate active factor VIII of similar specific activity. Furthermore, this hypothesis also offers an explanation for the increase in Mn^{2+} affinity observed for several of the A1 mutants. Thus some mutations may have resulted in an altered spatial separation between D125 (and D116) and His residue(s) H2082 and/or H2137 in C1 and this alteration may be favorable for Mn^{2+} coordination, yielding a higher affinity for the metal ion. This hypothesis is compatible with preliminary data suggesting that the effects of Ca^{2+} and Mn^{2+} on factor VIII activity generation are neither additive nor synergistic.

[0126] Overall, the stabilization that is proposed to result from metal ion binding near the A1-C1 junction may be necessary to provide proper orientation of factor VIIIa subunits within the factor Xase complex. Significant data indicate an extended interface between factor VIIIa and factor IXa, mediated by residues in A2 and A3 domains of the cofactor (Mertens et al., *Thromb. Haemost.* 82:209-217 (1999), which is hereby incorporated by reference in its entirety, for review). While residues in A3 appear to provide the majority of the binding energy for this interaction (Lenting et al., *J. Biol. Chem.* 269:7150-7155 (1994), which is hereby

incorporated by reference in its entirety), critical contacts between A2 subunit and the protease domain of factor IXa are required for cofactor function (Bajaj et al., *J. Biol. Chem.* 276:16302-16309 (2001), which is hereby incorporated by reference in its entirety). The latter is borne-out by the direct stimulation of factor IXa by the isolated A2 subunit (Fay et al., *J. Biol. Chem.* 273:19049-19054 (1998), which is hereby incorporated by reference in its entirety). While A1 subunit does not appear to contact factor IXa directly, inclusion of isolated A1 subunit results in a marked enhancement of the activity attributed to the isolated A2 subunit (Fay et al., *J. Biol. Chem.* 274:15401-15406 (1999), which is hereby incorporated by reference in its entirety). Thus A1 appears to function to orient A2 relative to the factor IXa protease domain. This property is further illustrated by truncation of A1 at R336 resulting in a dramatic loss in cofactor activity without significantly altering the inter-A1-A2 subunit affinity (Rosenblum et al., *J. Biol. Chem.* 277:11664-11669 (2002), which is hereby incorporated by reference in its entirety).

[0127] Factor VIII HC and LC associate in the absence of metal ion with moderate affinity ($K_d = 53.8 \pm 14.2$ nM) (Wakabayashi et al., *Biochemistry* 40:10293-10300 (2001), which is hereby incorporated by reference in its entirety) and inclusion of either Ca^{2+} or Mn^{2+} did not change the affinity of this interaction ($K_d = 48.7 \pm 15.4$ (Wakabayashi et al., *Biochemistry* 41:8485-8492 (2002), which is hereby incorporated by reference in its entirety) and 53.0 ± 17.1 nM (Wakabayashi et al., *Biochemistry* 42:145-153 (2003), which is hereby incorporated by reference in its entirety) in the presence of Ca^{2+} and Mn^{2+} , respectively). Thus the binding energy for interaction of HC and LC is likely derived from electrostatic and hydrophobic interactions between A1 and A3 domains. As described herein (*supra*), Ca^{2+} or Mn^{2+} binding the A1-C1 boundary region may create a fractional contribution to the total binding energy between HC and LC and thus remain undetected in the inter-chain affinity determination. Analysis of the kinetics of factor VIII activity generation of the HC/LC complex, associated in the absence of metal ions, following addition of Ca^{2+} yielded a series reaction pattern, suggesting that Ca^{2+} binding triggers certain conformational change(s) within the heterodimer to yield active factor VIII (Wakabayashi et al.,

Biochemistry 41:8485-8492 (2002), which is hereby incorporated by reference in its entirety). Conformational events suggested by the data presented herein may reflect the stabilization of the A1 110-126 region, followed by formation of a stable interface between this region and the region around H2137 in the C1 domain.

[0128] The presence of at least two Ca^{2+} sites have been identified in isolated A1 subunit by ITC following its treatment with EDTA. The large entropy change observed upon binding Ca^{2+} was consistent with a significant change in conformation of this domain as suggested herein (*supra*). The affinity value measured for the sites ($\sim 0.7 \mu\text{M}$) was similar to the value that was obtained monitoring the increase in specific activity ($1.18 \mu\text{M}$ for B-domain less wild type factor VIII). Furthermore, the fractional stoichiometry observed for occupancy of the isolated domain may suggest a dimerization of the subunit that is not observed with the intact heterodimer. The relationship of Ca^{2+} sites in the A1 domain with other sites in factor VIII has not yet been established. While passive removal was observed of a putative Ca^{2+} molecule(s) from the site proposed within residues 110-126, other metal ions likely remain associated as judged by the relatively high specific activity of the protein in solutions free from exogenous metal ions. Based upon the observation that pre-treatment of EDTA-treated factor VIII LC with Ca^{2+} was required to obtain reconstitution of functional factor VIII (Wakabayashi et al., *Biochemistry* 41:8485-8492 (2002), which is hereby incorporated by reference in its entirety), it is speculated that Ca^{2+} contained within sites in the LC may be retained in the absence of chelation. In support of this contention, preliminary data by ITC suggests the presence of multiple Ca^{2+} sites in the factor VIII LC.

[0129] Several drawbacks to a loss-of-function mutagenesis approach in the localization of Ca^{2+} -binding sites have been noted. These include mutation to an Ala eliminating total Ca^{2+} binding (Anderson et al., *Biochemistry* 36:11648-11654 (1997), which is hereby incorporated by reference in its entirety), or the elimination of charged residues far removed from a Ca^{2+} -binding site (Trigo-Gonzalez et al., *Biochemistry* 32:9826-9831 (1993); Ababou et al., *Biochemistry* 40:12719-12726 (2001), which are hereby incorporated by reference in their entirety) that result in reduced Ca^{2+} affinity. However, the results presented herein are further supported by a recent, similar approach applied to the Ca^{2+} -

binding site in factor V. The region comprised of residues 110-126 in factor VIII is highly homologous to residues 96-112 in factor V (Figure 5). Recent data generated following site-directed mutagenesis within this region indicates that E96, D102, and D111 appear to be crucial residues for the association of factor Va HC and LC (Zeibdawi et al., *Biochem. J.* 377:141-148 (2003), which is hereby incorporated by reference in its entirety), an interaction that is Ca^{2+} -dependent in factor Va (Krishnaswamy et al., *J. Biol. Chem.* 264:3160-3168 (1989), which is hereby incorporated by reference in its entirety). Results indicating a role for factor VIII residues E110, D116 and D126 in Ca^{2+} binding correspond to factor V residues E96, D102, and D111, respectively. These residues are conserved in all species of factor V and factor VIII identified to date. In addition, no role for residues E113, D115, and E124 in Ca^{2+} coordination has been shown, and these residues are not conserved in factor V. Thus the identification of selected, homologous residues as determined in two independent studies provides mutual support for the role of this region in contributing to Ca^{2+} -coordination sites in the protein cofactors.

Example 13 - Clotting Activity Following Saturation Mutagenesis at E113 of the Wild-Type Human Factor VIII

[0130] Factor VIII molecules bearing the indicated (see Figure 7) single point mutations at residue 113 were constructed according to the method described below. The factor VIII expression vector constructs (HSQ-MSAB-NotI-RENeo) were transfected into confluent Cos-7 cells using FuGene6 (Roche, Indianapolis, IN). After 1 day, the medium was changed to AIM-V (Invitrogen) and cultured for an additional 2 days. Conditioned medium containing the expressed factor VIII was collected and factor VIII activity was measured using a one-stage clotting assay. Activity is presented relative to a transfected wild-type control representing a value of (1). Results from this analysis show that mutant E113A possesses significantly greater clotting activity than that observed for the wild-type protein. Furthermore, several other point mutations at this position, including E133L, E113I, E113V, E113N, E113G and E113M show similar or modestly greater clotting activity compared with wild-type.

[0131] The clotting activity of the thrombin-activated factor VIII mutant E113A is shown in Figure 8 below, which demonstrates that both factor VIII and factor VIIIa forms of the mutant demonstrate an ~2-fold increased activity.

Example 14 – Experimental Methods for Determining that Factor VIII:E113A Represents a High Specific Activity Factor VIII

[0132] Examples 1-12 above identify an acidic-rich segment in the A1 domain of factor VIII (residues 110-126) that functions in the coordination of Ca^{2+} , an ion necessary for cofactor activity (Wakabayashi et al., *J. Biol. Chem.* 279:12677-12684 (2004), which is hereby incorporated by reference in its entirety). Using Ala-scanning mutagenesis, it was determined that replacement of residue E113 with Ala yielded a factor VIII point mutant that possessed an ~2-fold increased affinity for Ca^{2+} as compared with wild type, suggesting that this residue did not directly contribute to Ca^{2+} coordination but rather modulated the affinity of the ion at this site. Furthermore, the E113A factor VIII possessed twice the specific activity of wild type as determined by a one-stage clotting assay, whereas a similar specific activity was observed using a chromogenic assay. As described in this Example 14, the activity of factor VIII forms following saturation mutagenesis at residue 113 and the thrombin activation of the E113A form. Factor Xa generation assays performed on synthetic membrane and platelets are employed to determine kinetic and binding parameters for factor Xase comprised of the factor VIII E113A and wild type.

[0133] Factor VIII molecules bearing single point mutation of Glu113Ala were constructed from B domainless-factor VIII cDNA as described in Example 1 above, (using HSQ-MSAB-NotI-RENeo, obtained from Dr. Pete Lollar and John Healey). The factor VIII expression vector constructs were transfected in BHK cells and the mutant proteins were purified by SP-sepharose.

[0134] Saturation mutagenesis and the transient expression of factor VIII, substituting every amino acid except Asp for residue 113 was constructed and transiently expressed in COS-7 cells. Factor VIII activity in the conditioned medium (2 day) was measured by a one-stage clotting assay.

[0135] Factor VIII cofactor activity, factor IXa-factor VIIIa affinity, and kinetic parameters were determined using factor Xa generation assays. Reactions

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were performed in the presence of either phospholipid vesicles, non-activated platelets, or platelets activated by SFLLRN-amide (50 μ M).

[0136] As shown in Figure 7, E113A possessed the greatest increase in activity relative to wild type (~3-fold). Substitution with Gly, Asn, or Met yielded modest activity increases (<50%), while Leu, Ile, Val, Pro, Cys, and Arg showed little if any effect. On the other hand, Lys, Gln, Trp, Tyr, Pro, His, Phe, Ser, and Thr were observed to be somewhat detrimental to activity with the latter three showing the greatest reductions in activity (at least 50%).

[0137] As shown in Figure 8, factor VIII E113A and wild type (10 nM each) were activated by thrombin (5 nM) and activity was monitored by one-stage clotting assay. Activity is expressed as a ratio to the non-activated factor VIII activity at time 0. Both forms were activated ~40-fold, which occurred over a similar time course (Figure 8). Furthermore, at all time points, E113A possessed about twice the activity as wild type. In addition, both activated forms decayed at similar rates suggesting that this mutation did not alter in the affinity of the A2 subunit within the factor VIIIa molecule.

[0138] As shown in Table 3 (below), both wild type and E113A bind to factor IXa with high affinity (K_d ~5 nM) on phospholipid vesicles with <10% increase in k_{cat} . However, on the platelet surface, wild type binds factor IXa with lower affinity (K_d ~20-25 nM) while E113A binding was unchanged (K_d ~6 nM).

Table 3: Summary of Binding and Kinetic Parameters for Factor Xase Complexes**On Phospholipid Vesicles:**

	Wild Type (WT)	E113A
K_d (nM)	4.6 ± 0.3	5.0 ± 0.7
K_m (nM)	23.8 ± 3.1	32.3 ± 2.2
K_{cat} (min^{-1})	225 ± 6	240 ± 15

On Activated Platelets:

	Wild Type (WT)	E113A
K_d (nM)	20.3 ± 5.1	6.0 ± 1.4
V_{max} (nMmin^{-1})	23.8 ± 2.9	18.9 ± 1.8
K_m (nM)	14.3 ± 0.8	18.0 ± 1.1
V_{max} (nMmin^{-1})	10.4 ± 0.2	14.7 ± 0.3

On Non-Activated Platelets:

	Wild Type (WT)	E113A
K_d (nM)	25.6 ± 2.5	5.7 ± 0.6
V_{max} (nMmin^{-1})	3.1 ± 0.2	2.5 ± 0.1
K_m (nM)	16.7 ± 7.2	41.9 ± 16.8
V_{max} (nMmin^{-1})	0.4 ± 0.1	1.2 ± 0.2

[0139] The activation of platelets resulted in increases in the V_{max} values, while K_m values were unchanged. The apparent increased V_{max} for E113A compared with wild type in Figure 10B reflects sub-saturating levels of the factor VIIIa forms. A ~2-fold increase was observed in the activity of factor VIII E113A in a one-stage clotting assay. This increased activity was not likely a result of increased affinity for Ca^{2+} , since assays were performed at saturating Ca^{2+} levels.

[0140] Saturation mutagenesis at position 113 (Figure 7) revealed that substitution at this position with relatively small, nonpolar residues was well-tolerated, whereas replacement with a number of polar or charged residues was detrimental to activity. Thus residue 113 appears to contribute, directly or indirectly to factor VIII function. Ala-substitution yielded the greatest activity value.

[0141] Similar rates of activation and inactivation of E113A as observed for factor VIII wild type (Figure 8) indicated that altered interactions with thrombin or the inter-subunit affinity factor VIIIa E113A do not contribute its increased activity.

[0142] Results from factor Xa generation assays performed on synthetic phospholipid vesicles showed the mutant possessed similar values for specific activity, K_m for substrate factor X, k_{cat} for factor Xa generation and K_d for factor IXa as compared with factor VIII wild type (Figures 9A-B). However, using platelet surfaces, significantly higher affinity was observed for the E113A – factor IXa interaction compared with that for WT (Figures 10A-B).

[0143] Since low levels (sub-nM) of factors VIIIa and IXa are generated during clotting in plasma, the enhanced affinity of factor VIII E113A for factor IXa may represent a novel factor VIII form for the treatment of hemophilia.

[0144] The factor VIII mutation E113A enhances the affinity for factor IXa on physiologic surfaces. This alteration may reflect the increased specific activity of E113A measured in a one-stage clotting assay where low levels of factor IXa may be generated.

[0145] Atomic surface modeling results show that the 110-126 region resides within A1 domain in close proximity to C1 domain but far removed from both surface and factor IXa interactive sites. Thus, indirect mechanisms appear to be involved in the surface-dependent modulation of factor IXa binding affinity due to the E113A mutation.

[0146] Although preferred embodiments have been depicted and described in detail herein, it will be apparent to those skilled in the relevant art that various modifications, additions, substitutions, and the like can be made without departing from the spirit of the invention and these are therefore considered to be within the scope of the invention as defined in the claims which follow.